AFRL-RX-TY-TP-2009-4532

PREPRINT

EVALUATION OF BLAST RESISTANT RIGID WALLED EXPEDITIONARY STRUCTURES

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MARCH 2009

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
31-MAR-2009	Technical Paper PREPRINT	01-JAN-2008 -- 31-MAR-2009

4. TITLE AND SUBTITLE

Evaluation of Blast Resistant Rigid Walled Expeditionary Structures (PREPRINT)

5a. CONTRACT NUMBER FA4819-07-D-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 99999F

6. AUTHOR(S)

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5d. PROJECT NUMBER 4915

5e. TASK NUMBER F0

5f. WORK UNIT NUMBER Q210FA72

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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Tyndall Air Force Base, FL 32403-5323

10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RXQF

11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RX-TY-TP-2009-4532

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Ref AFRL/RXQ Public Affairs Case #09-040. Submitted to 13th International Symposium on the Interactions of the Effects of Munitions with Structures, 10-15 May 2009, Bruhel, Germany. Document contains color images.

14. ABSTRACT

Blast and fragmentation resistance of expeditionary shelters has become of great interest given the current threat environment. One such structure now being considered for deployment utilizes an ISO container sized steel frame with infill panels. The panels consist of a lightweight extruded polystyrene core sandwiched between two galvanized, light-gauge steel sheets. An investigation was conducted into the blast and fragmentation resistance of this new type of shelter and a direct comparison was made to that of a typical ISO container shelter currently deployed in theater. The static resistance function of the panel system was determined in the laboratory via two experimental methods. A 16-point loading tree simulating a uniform load was utilized on a variety of full-scale panel cross-sections representing seven panel configurations. A vacuum chamber was employed to accomplish static full-scale wall testing. Laboratory resistance data was used to model the dynamic response of the panel system using a single-degree of freedom (SDOF) analysis. Accuracy of the analytical model was verified via three arena blast experiments, each of which included an instrumented ISO container for direct data comparison.

15. SUBJECT TERMS

rigid walled, single-degree of freedom, SDOF, steel encased foam core panels, SEFCP

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	19	Dinan, Robert
					19b. TELEPHONE NUMBER *(Include area code)*

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Evaluation of Blast Resistant Rigid Walled Expeditionary Structures

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1. Abstract

Blast and fragmentation resistance of expeditionary shelters has become of great interest given the current threat environment. One such structure now being considered for deployment utilizes an ISO container sized steel frame with infill panels. The panels consist of a lightweight extruded polystyrene core sandwiched between two galvanized, light-gauge steel sheets. An investigation was conducted into the blast and fragmentation resistance of this new type of shelter and a direct comparison was made to that of a typical ISO container shelter currently deployed in theater.

The static resistance function of the panel system was determined in the laboratory via two experimental methods. A 16-point loading tree simulating a uniform load was utilized on a variety of full-scale panel cross-sections representing seven panel configurations. A vacuum chamber was employed to accomplish static full-scale wall testing. Laboratory resistance data was used to model the dynamic response of the panel system using a single-degree of freedom (SDOF) analysis. Accuracy of the analytical model was verified via three arena blast experiments, each of which included an instrumented ISO container for direct data comparison.

2. Introduction

The focus of this investigation was to determine the blast resistance of a newly developed rigid walled expeditionary shelter. The shelter is based on a structural ISO frame with in-fill panels. These ISO sized modular shelters are designed to be transported to the field using existing infrastructure. Modules are shipped with floor and ceiling panels pre-installed. Once in place, the frames can be stacked up to three units high. After configuring the desired number of frames, in-fill panels are installed along the perimeter (Figure 1). Currently, 8x20 and 8x40 foot frames are produced by the manufacturer. Module weights are approximately 6,000 and 12,000 lbs respectively.

Originally designed to replace structural sub-floors and roof truss systems, the in-fill Steel Encased Foam Core Panels (SEFCP) consist of a lightweight extruded polystyrene core adhesively bonded to 20 gauge steel skins. The sides of the panels are enclosed with roll-formed steel frame with an interconnecting edge profile for added support. Panels are 4 inches thick, 4 feet wide and are available in lengths up to 24 feet. The panels offer an R-21.5 insulation value and weigh approximately 5 lb/ft^2.

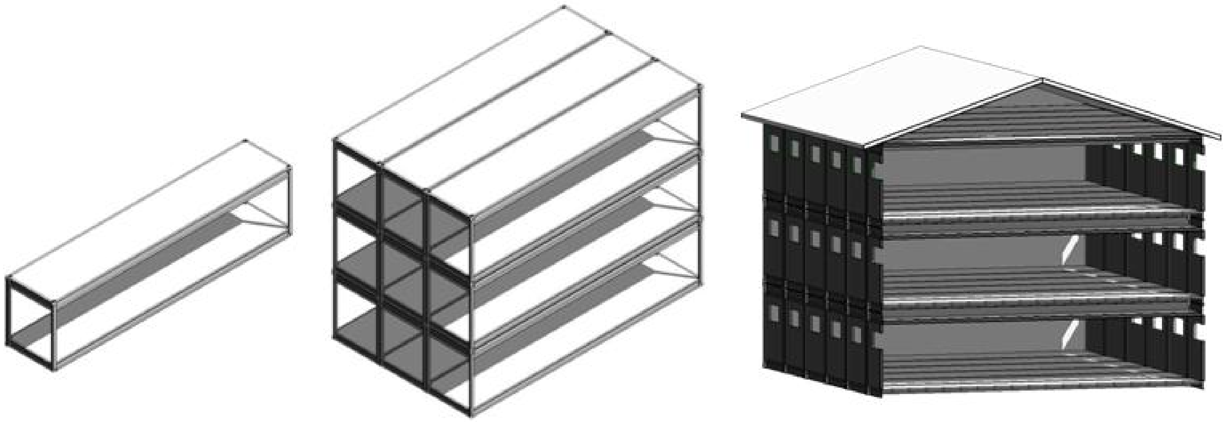

Figure 1. Phases of SEFCP modular shelter construction.

3. SDOF Modeling

In blast-resistant design and research, structures are often analyzed using a Single Degree of Freedom (SDOF) analytical model to approximate structural response [2, 3, 4]. The SDOF methodology involves simplifying a structure or component down to a single degree of freedom which can be analyzed efficiently. This is done by assuming a deformed shape of the system. The assumed shape can be determined through static deflection analysis or experimentation under uniform loading. The point of maximum deflection under static loading equates to the SDOF predicted response. Assuming the deflected shape remains constant, the system can be modeled using this single point of motion [1].

The response of the system is predicted using an explicit set of equations to solve the equation of motion. Traditionally, the SDOF model used in structural dynamics employs a simple spring-mass system subjected to an externally applied load. The same principle is used in blast design and research with one addition. While spring stiffness (k) accounts for elastic deformations, more information is required to predict plastic behavior. The prevailing method for defining the resistance to motion of a system is to first define its static resistance function. The static resistance function is defined by the load-deflection curve of the system under static loading. Resistance equates to the load required to achieve a given deflection. In the elastic range, resistance correlates directly to structural component stiffness. Beyond the elastic region, spring stiffness is correlated to a system's resistance to loading for a given deflection [1].

Often SDOF models are done with simplified versions of the static resistance function taking into account only an elastic and perfectly plastic region. But more detailed static resistance functions are able to provide higher quality input for the SDOF response. To advance the use of new systems for blast design, it is necessary to develop engineering-level methodologies. Engineering-level static resistance functions utilizing engineering mechanics can be developed and verified using laboratory static testing. In this paper, the static resistance function is developed using laboratory static testing of full-scale components and systems, as described next.

4. Static Resistance Function

The static resistance of the SEFCP's was determined using full-scale component-level and system-level static experiments using a 16-point loading tree and vacuum chamber respectively. Load tree testing is described next, followed by vacuum chamber testing.

4.1. Load Tree Testing

A 16 point loading tree (Figure 2) was used to determine the static resistance of fourteen SEFCP cross-sections. After being loaded into the tree, samples were instrumented with string potentiometers at the quarter points. These instruments were used to measure deflections and in turn characterize the shape function of the panel. Each sample was loaded in displacement control at 0.5 in/min. Both deflection and load were recorded and the samples resistance to a given load was determined.

Figure 2. SEFCP being tested in load tree.

A total of seven configurations were tested in the loading tree with special emphasis on the commercially available connection method shown in Figure 3. Seen in the figure is a 3/16" angle welded to the floor beam of the structural ISO frame. The panels rest on this angle and are secured with mechanical fasteners 12 inches on center. The same connection method is used to secure the top of the panel. Two panel configurations were tested using this connection method. The first was a center section of the composite panel measuring 18 x 88.5 inches. This will be

referred to as the "No Seam" configuration. The second configuration was also 18 inches wide, but made up of two 9 inch panel sections joined via their interconnecting edge profiles. This will be referred to as the "Seamed" connection.

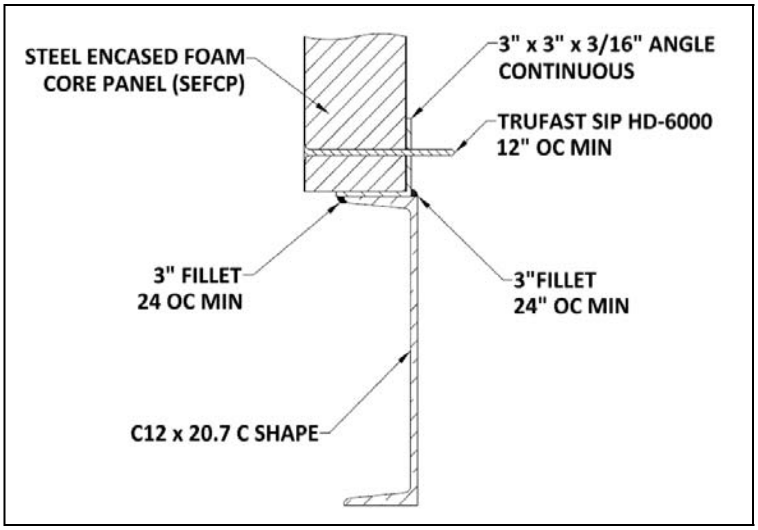

Figure 3. Commercially available connection method of SEFCP panels.

Characteristic resistance functions for each test configuration can be seen in Figure 4. The figure shows that as the samples are displaced, resistance to that displacement increases rapidly. This rate of increase is defined as the spring stiffness of the panel. Eventually, the elastic limit (y_{el}) of the sample is reached and maximum resistance is achieved (R_{max}). This equates to the maximum flexural capacity of the sample. When displaced beyond this limit, the sample's resistance decreases dramatically as it buckles under the load. However, the connections securing the top and bottom of the sample do not fail. As the sample is displaced even further, a membrane stress develops in the sample as it begins to behave much like a cable. Eventually, this membrane resistance begins to exceed the bearing capacity of the panel and the sample fails completely ($y_{failure}$).

When comparing the performance of the Seam and No Seam configurations, resistance varies significantly (Figure 4). The cold formed edge profiling of the Seamed configuration increased maximum resistance by 45%. Stiffness of the Seamed panel is also increased (26%). As the No Seam panel reaches its flexural capacity, resistance decreases dramatically. In contrast, the added structure of the Seamed panel's edge profiling offers significant resistance even after buckling. Failure limits for both configurations are similar.

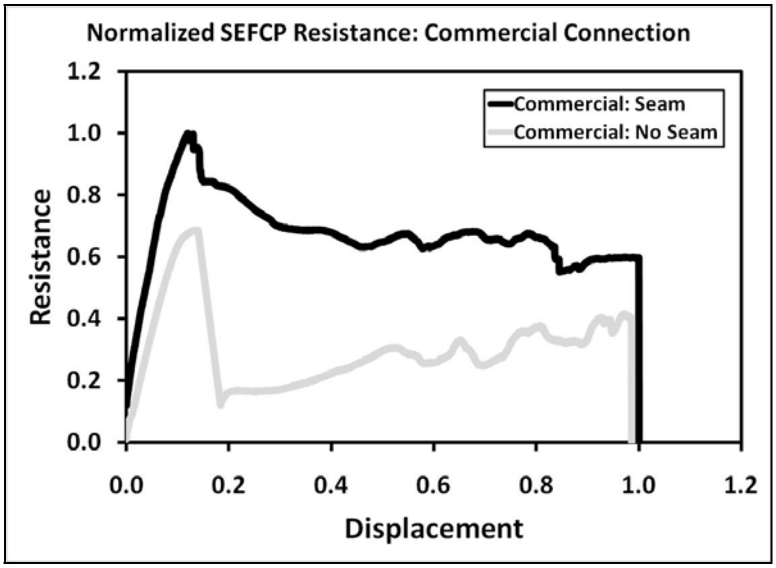

Figure 4. SEFCP resistance functions from load tree testing.

4.2. Vacuum Chamber Testing

The loading tree is limited to panel widths fewer than 20 inches. This poses a problem for testing non-uniform walls such as those constructed of SEFCP panels. As previously stated SEFCP panels are four feet in width and have interconnecting edge profiles. It was shown during load tree testing that these edge profiles add significantly to the maximum resistance of the panels. To eliminate this discontinuity, it was desirable to test a full-scale system of panels in a vacuum chamber.

Three walls were tested in the chamber. Each wall consisted of three full-width panels measuring 88.5 inches in length. To center the panels in the chamber, reinforced knee walls were constructed. Panels were connected to the knee walls using the commercially available connection method. After installation of the composite panels, metal flashing was applied along their perimeter to fill any significant gaps between the wall and the chamber. Finally, a rubber membrane was placed over the wall and secured to the chamber via a steel frame. Once a proper seal was made, air was evacuated from the chamber. Vacuum chamber test set-up can be seen in Figure 5. String potentiometers were utilized to measure mid and quarter-point deflections of the center panel as well as mid-point deflections of the two outer panels. Internal pressure and deflections were recorded. A resistance function was calculated from this data.

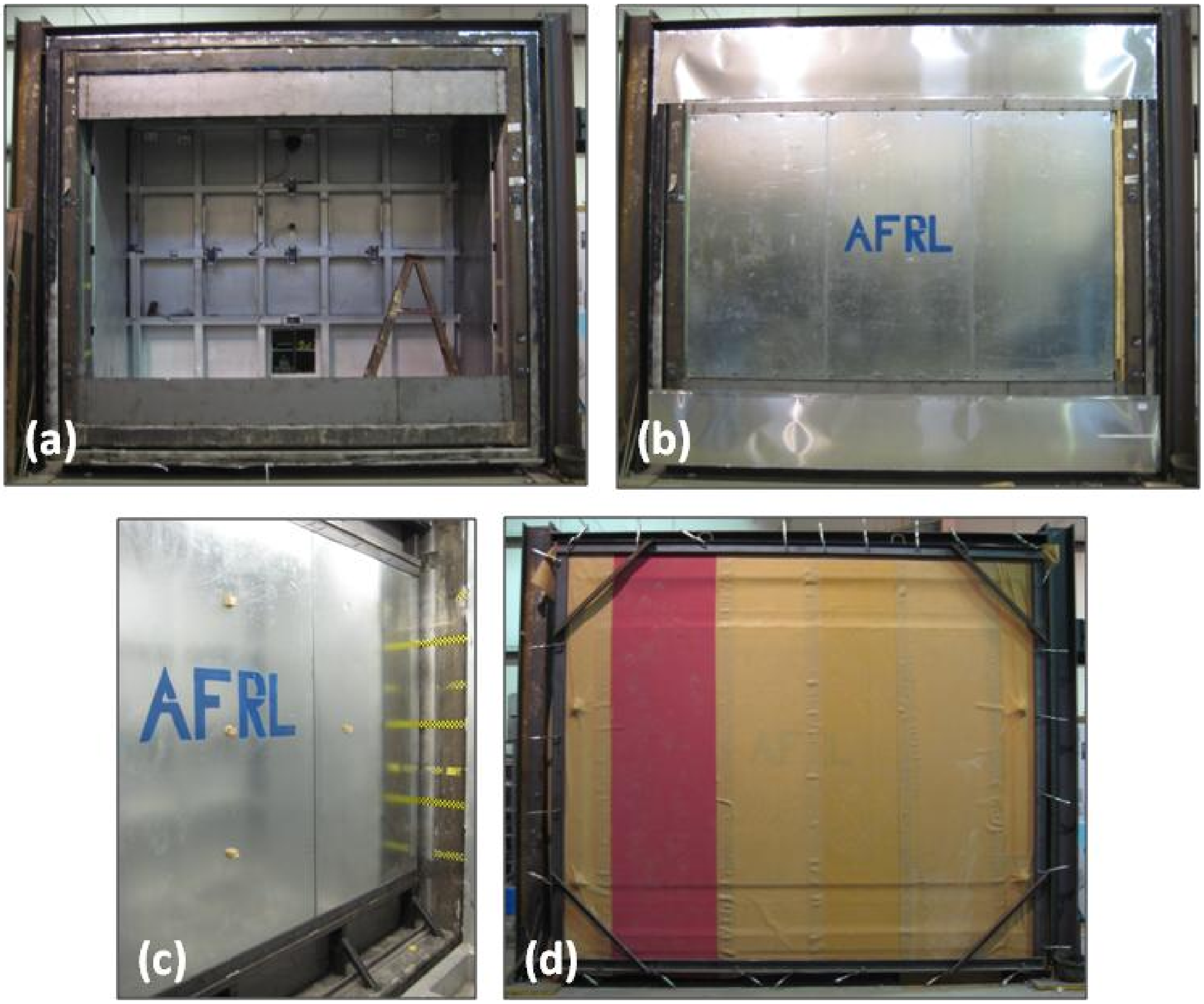

Figure 5. Vacuum chamber set-up: (a) chamber face & knee walls, (b) installed panels & metal flashing, (c) internal view with string potentiometers, (d) rubber membrane.

Resistance functions for the 3 walls tested in the vacuum chamber are seen in Figure 6. Stiffness for the three walls closely aligns with the No Seam configuration tested in the load tree although the maximum resistance approaches that of the Seamed panels. The most apparent difference between the vacuum chamber and load tree data is the lack of a plastic deformation phase. Unlike the loading tree, vacuum chamber testing is load controlled. Load on the panels is steadily increased as air is evacuated from the chamber. As the panels buckle, their ability to resist the load is reduced and a catastrophic failure ensues.

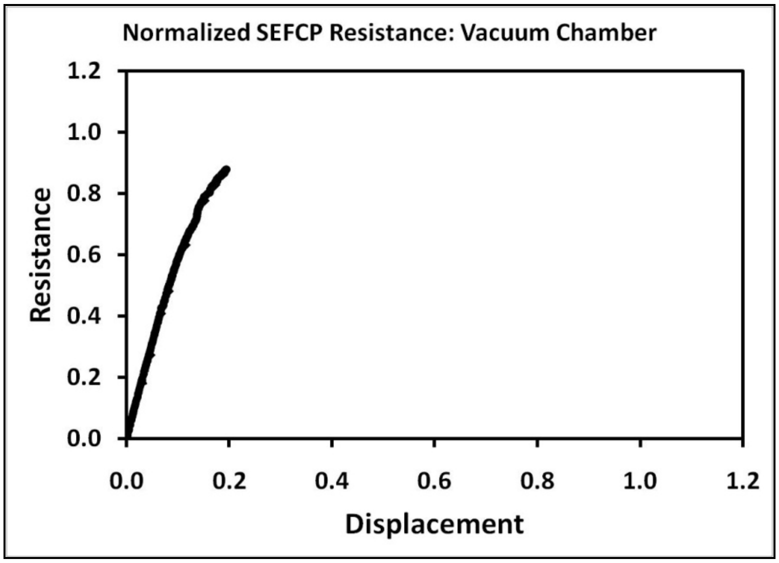

Figure 6. SEFCP resistance functions from vacuum chamber testing.

4.3 Composite Resistance

It was determined that a composite resistance function should be compiled based on data from both test methods. The elastic portion of this new resistance function would consist solely of vacuum chamber data as it was the result of full-scale wall tests. As previously mentioned, the plastic portion of the resistance function could not be obtained from vacuum chamber testing. This portion of the function would consist of load tree data from both Seam and No Seam configurations and be a weighted average based on tributary area. Failure limit was determined by averaging the failure limits of all load tree tests. The resulting composite resistance function and the data from which it came are plotted in Figure 7.

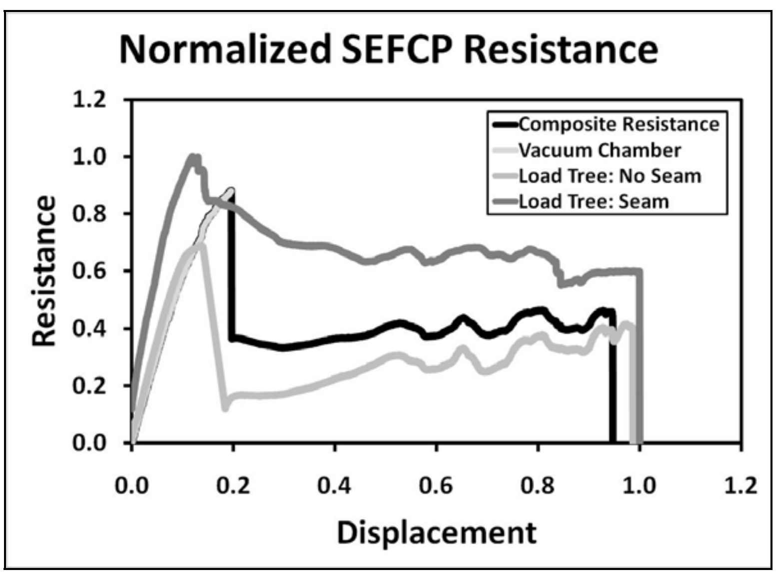

Figure 7. Normalized SEFCP composite resistance.

4.4. Improving Panel Resistance

The failure of the commercially-connected panels was controlled by the capacity of the connection. The inherent strength and ductility of steel panel faces were not utilized to their potential during the tension membrane resistance. Therefore, in this section simple connection modifications are recommended and evaluated to improve the blast resistance of the panels. Two additional connection types were investigated using the load tree, the first of which will be referred to as the AFRL modified connection and the second will be referred to as the fixed connection. The results of these two modifications are presented next.

4.4.1 AFRL Modified Connection

The modified connection consisted mainly of two 0.125-inch plates. The first plate wrapped around the panel and extended 8 inches along its face. The second plate was 10 inches in length. It extended 8 inches along the back face of the panel and overlapped the c-shape by 2 inches. These plates created deep channels for the panels to rest in and were welded to the floor and roof C-shapes. The panels themselves were secured to the channel with two alternating rows of mechanical fasteners 4.5 inches on center and 3 inches apart. The intention of this design was to create a practical connection that balanced the shear failure of the fasteners with the bearing failure of the panel's steel skin. The modified connection detail is shown in Figure 8.

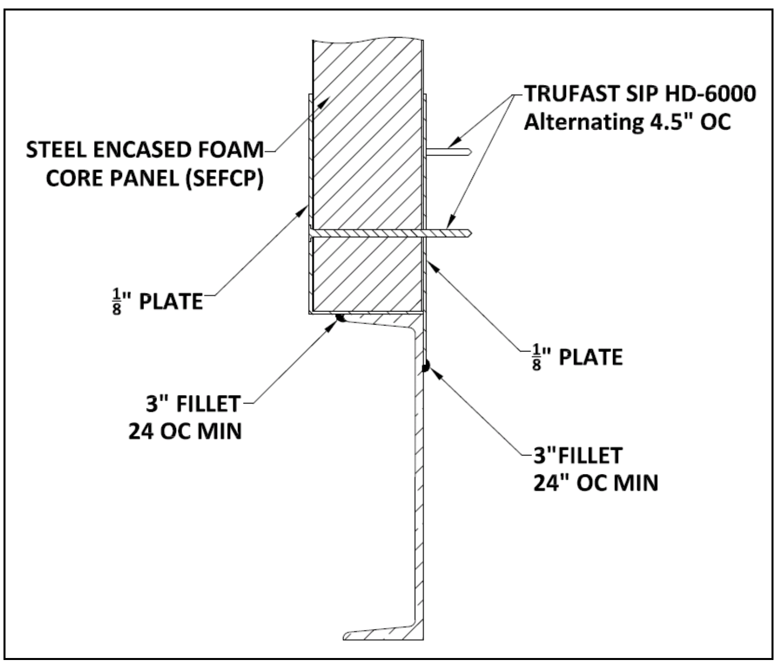

Figure 8. AFRL modified connection detail.

Resistance data for the AFRL modified connection as well as a commercially available connection is shown in Figure 9. The plot shows a dramatic difference between the two designs. Stiffness for both connections remains largely unchanged. This is also true for the elastic limit. However, the difference in maximum resistance between the two methods is quite large. By modifying the connection, maximum resistance is increased nearly 200%. The failure limit of

the panel also increased 135%. In addition, the strain energy of the modified panel was 285% higher than that of the commercially-connected panels

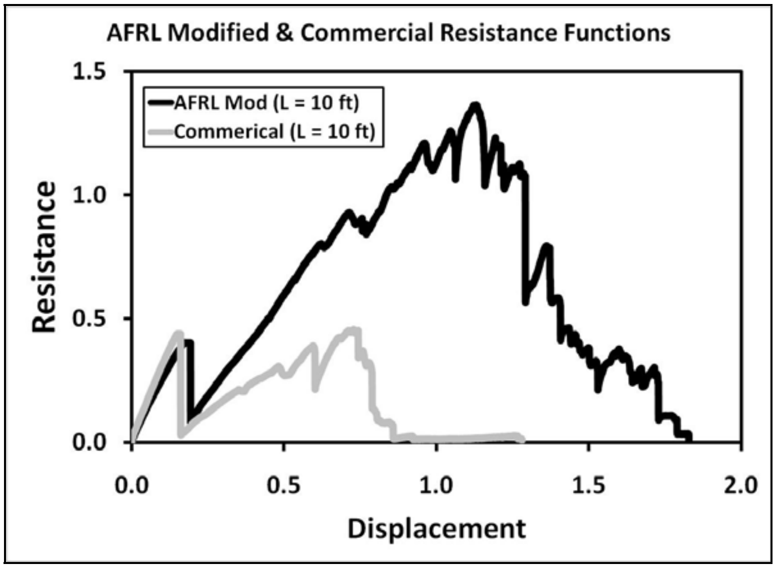

Figure 9. Normalized resistance of AFRL modified and commercially available connections.

4.4.2. Fixed Connection

For future research, it was desirable to determine the maximum membrane capacity in the panel. To achieve this, a robust connection method was developed based on the AFRL modified design. For the new design the 0.125-inch plate was replaced by a 0.25-inch plate. The resulting channel was welded to the c-shape. Additionally, the channel was welded to the panel skins and mechanical fasteners were neglected. Connection details are shown in Figure 10.

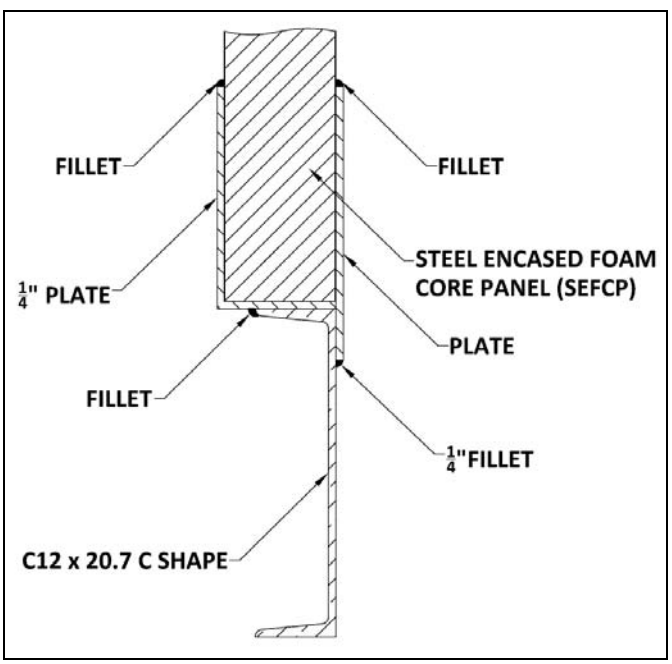

Figure 10. Fixed connection detail.

While not practical, this connection method did prove robust enough to allow for the maximum membrane stress to develop in the panel. The connection allowed for enough stress to build in the panel for the steel skins to fail in tension. Resistance data obtained from this test is shown in Figure 11. While panel stiffness is similar to the commercial connection, all other parameters are greatly increased. The failure limit of the panel increases 159% while the maximum resistance increases 732%. In addition, the strain energy of the modified panel was 1186 % higher than that of the commercially-connected panels.

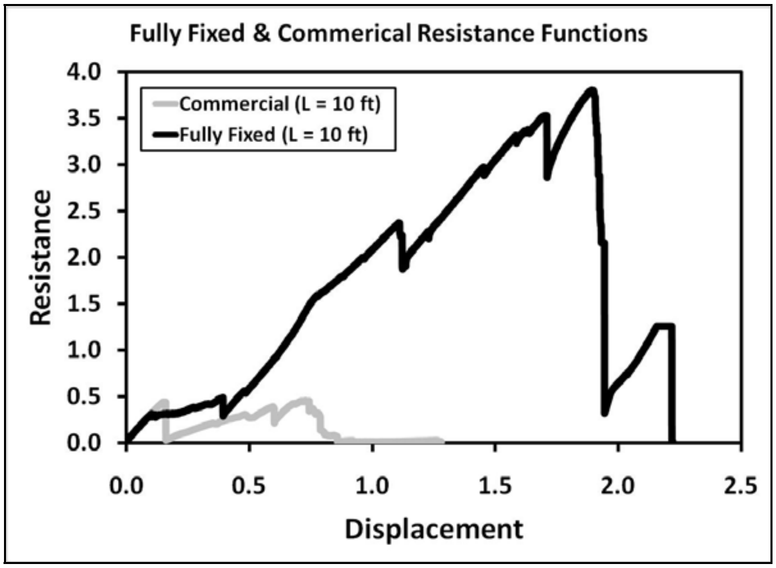

Figure 11. Normalized resistance of fixed and commercially available connections.

5. Field Validation of SDOF Model

Three full-scale blast tests were conducted to validate the empirical model. Charge weights and stand-off distances were determined using model predictions and Department of Defense (DoD) standards. While charge weight remained constant, standoff distance was decreased for each successive test.

Experimentation with a complete system of SEFCP shelter s was cost prohibitive. Instead, this evaluation concentrated on a single module measuring 20 x 8 x 9.5 feet. For comparison purposes, a 20 x 8 x 8 foot ISO container (Conex shelter) was also included in each test. With minor alterations, this analogous system is seeing widespread use in theater as a modular expeditionary shelter. Including the Conex shelter in this evaluation allowed for direct data comparison between the two systems.

5.1. Test Set-Up

The SEFCP and Conex shelters were identically instrumented for each test. Each structure contained an internal pressure gauge and video camera. Deflection gauges were affixed to the front wall and ceiling as well. Finally, an external reflected pressure gauge was centered on the face of each structure (Figure 12). High-speed cameras were placed behind each structure and angled to capture the frontal deflections of each shelter. A free-field pressure gauge was

centered between the structures (Figure 13). Stakes were place at the corners of each shelter to ensure any translation was accounted for.

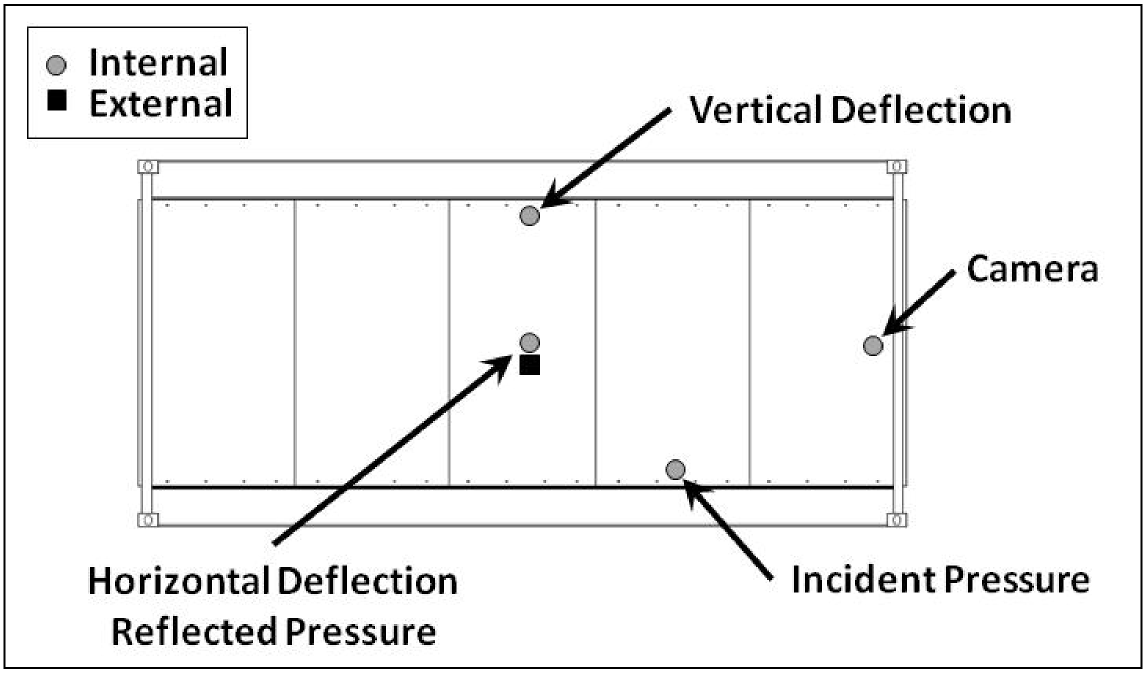

Figure 12. Shelter instrumentation.

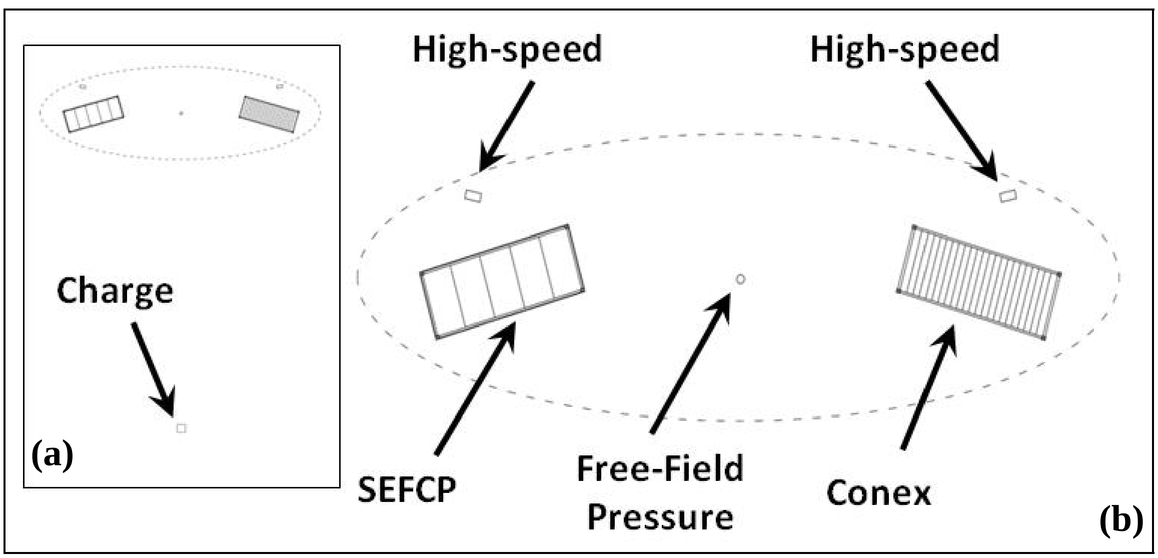

Figure 13. Blast arena layout: (a) overall plan view; (b) close-up view of both shelters tested.

5.2. Blast Test Results

A normalized data summary from each blast test is show in Table 1. SDOF model accuracy compared to actual SEFCP deflections are also given in the table. The results are also represented graphically in Figure 14. Blast results for each test are described next.

Table 1. Normalized blast test results and SDOF model accuracy.

Test	Reflected Pressure	Reflected Impulse	SEFCP Deflection	Conex Deflection	Model Accuracy (% Error)
Blast Test I	0.522	0.534	0.129	0.431	10.0
Blast Test II	0.687	0.716	0.182	0.624	25.9
Blast Test III	1.000	1.000	0.376	1.000	1.3

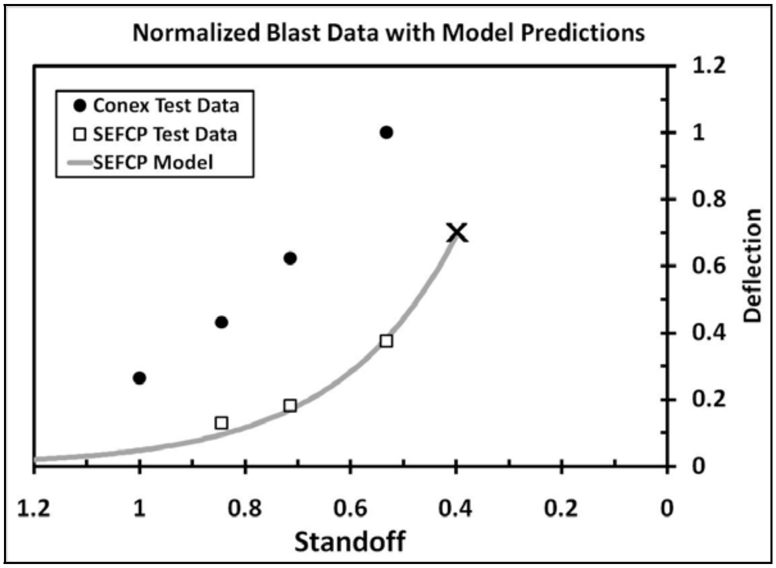

Figure 14. Normalized blast data with SDOF predictions for SEFCP shelters.

5.2.1. Blast Test I

The results of Blast Test I are summarized in Figure 15. As expected, reflected pressure and impulse were nearly identical for the similarly sized structures as seen in Figures 15a and 15b. Front wall deflection for the SEFCP and Conex shelters are show in Figure 15c. The SEFCP shelter outperformed the Conex with a 70% less inward deflection and 15% less outward deflection. Predicted and actual SEFCP deflection data is plotted in Figure 15d. The SDOF model closely predicts inward wall deflection to within 10%. Note how the inward deflection prediction ceases at maximum deflection and no outward prediction is made. Resistance of the panels on which the analytical model is based was determined only under positive loading; hence any predictions beyond this point will be inaccurate. Post-test damage of the SEFCP shelter was not apparent, while minor rippling of the Conex's front face was observed. Neither structure showed evidence of translation.

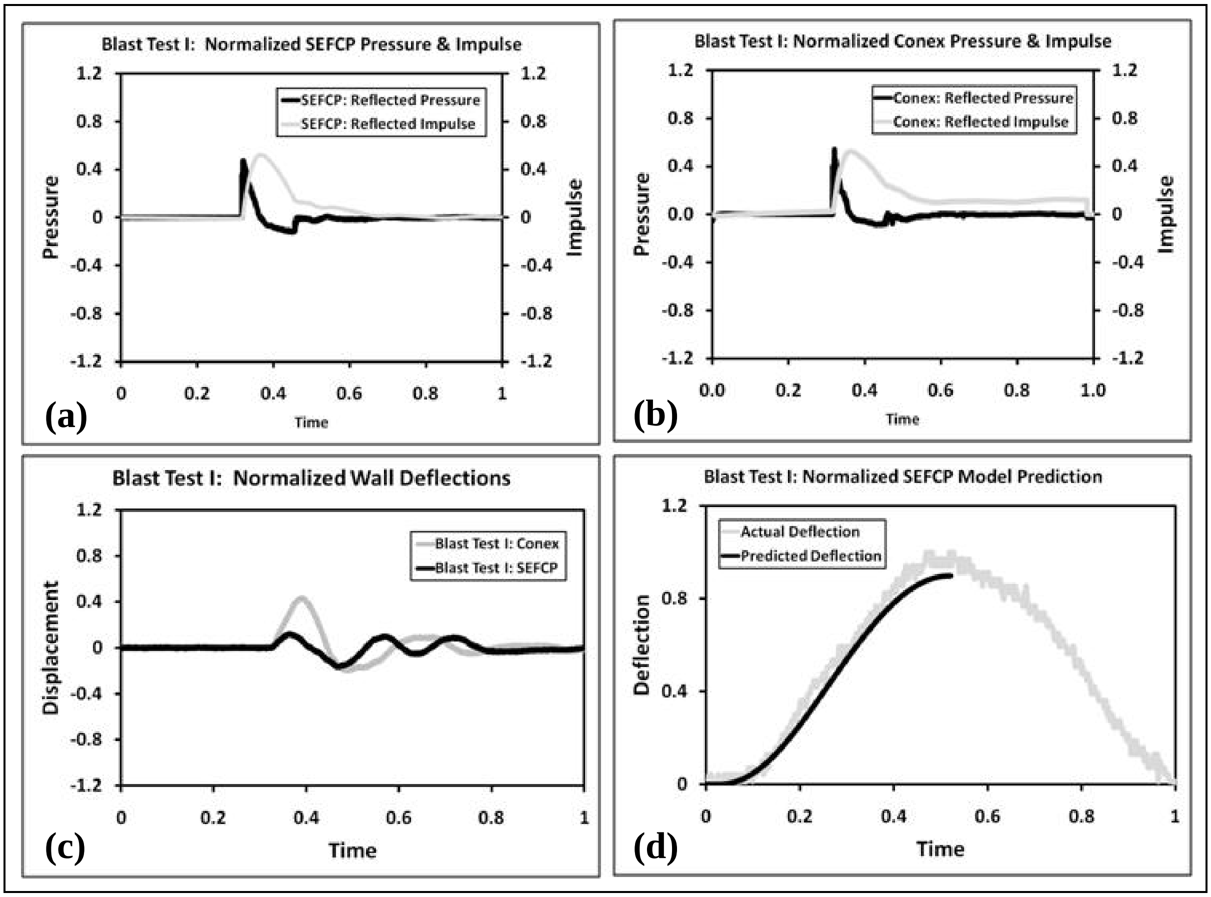

Figure 15. Blast Test I data: (a) SEFCP reflected pressure & impulse, (b) Conex reflected pressure and impulse, (c) Wall deflections, (d) SDOF model prediction.

5.2.2. Blast Test II

Standoff distance for Blast Test II was decreased 16% and the charge weight was kept constant. As a result, reflected pressure and impulse on the structures increased by approximately 34%. The SEFCP once again outperformed the Conex in terms of inward deflection, displacing nearly 71% less than the ISO container (Figure 16c). Outward deflections of the two shelters are similar. Model accuracy decreased to 26% error for the relatively small wall deflection seen in Blast Test II (Figure 16d). Again, post-test damage of the SEFCP shelter was not apparent, while minor rippling of the Conex's front face was observed. Neither structure showed evidence of translation.

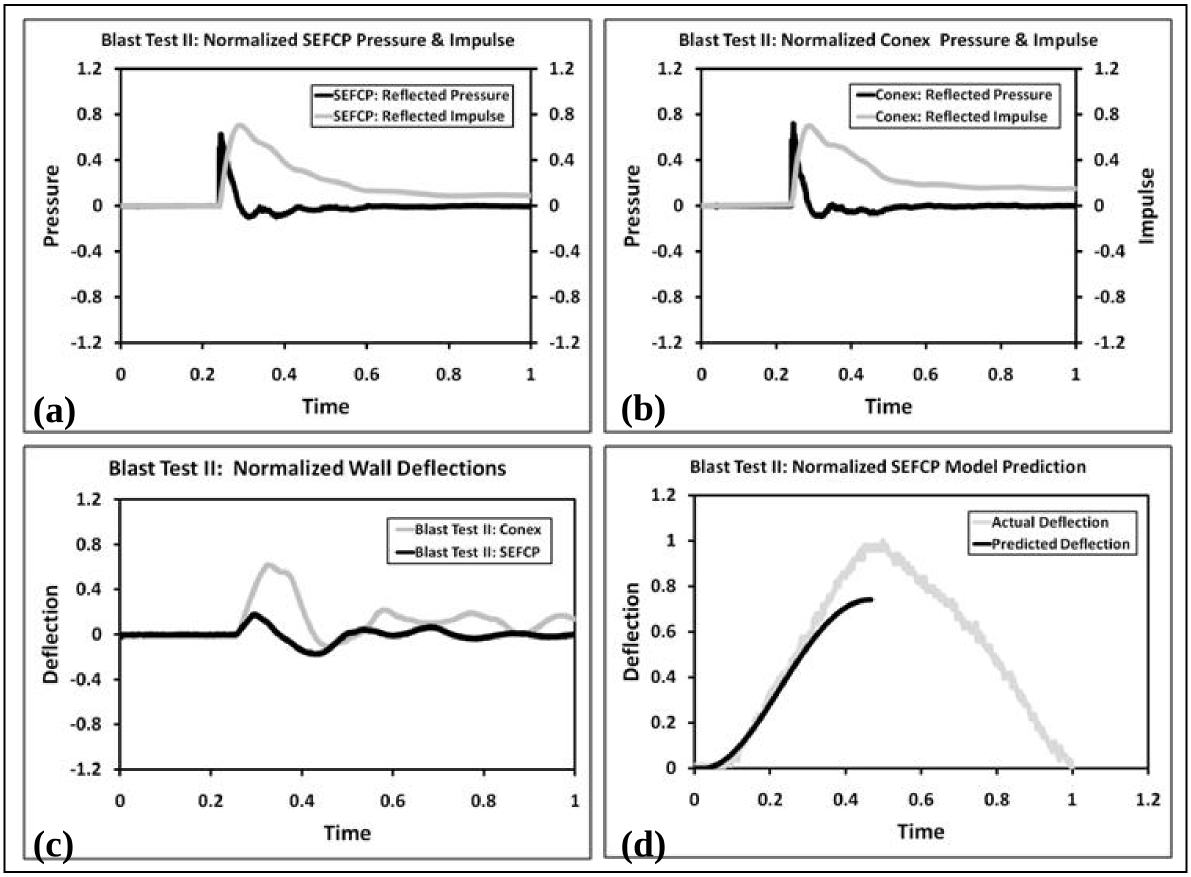

Figure 16. Blast Test II data: (a) SEFCP reflected pressure & impulse, (b) Conex reflected pressure and impulse, (c) Wall deflections, (d) SDOF model prediction.

5.2.3. Blast Test III

Standoff distance was decreased an additional 26% for Blast Test III while charge weight was again kept constant. Reflected pressures were similar for both shelters and approximately 46% higher than Blast Test II. Reflected impulse increased approximately 40%. Once again the SEFCP deflected inward significantly less (62%) than the Conex while outward deflections were similar. Percent error for the SDOF model was minimal at approximately 1.5% (Figure 17).

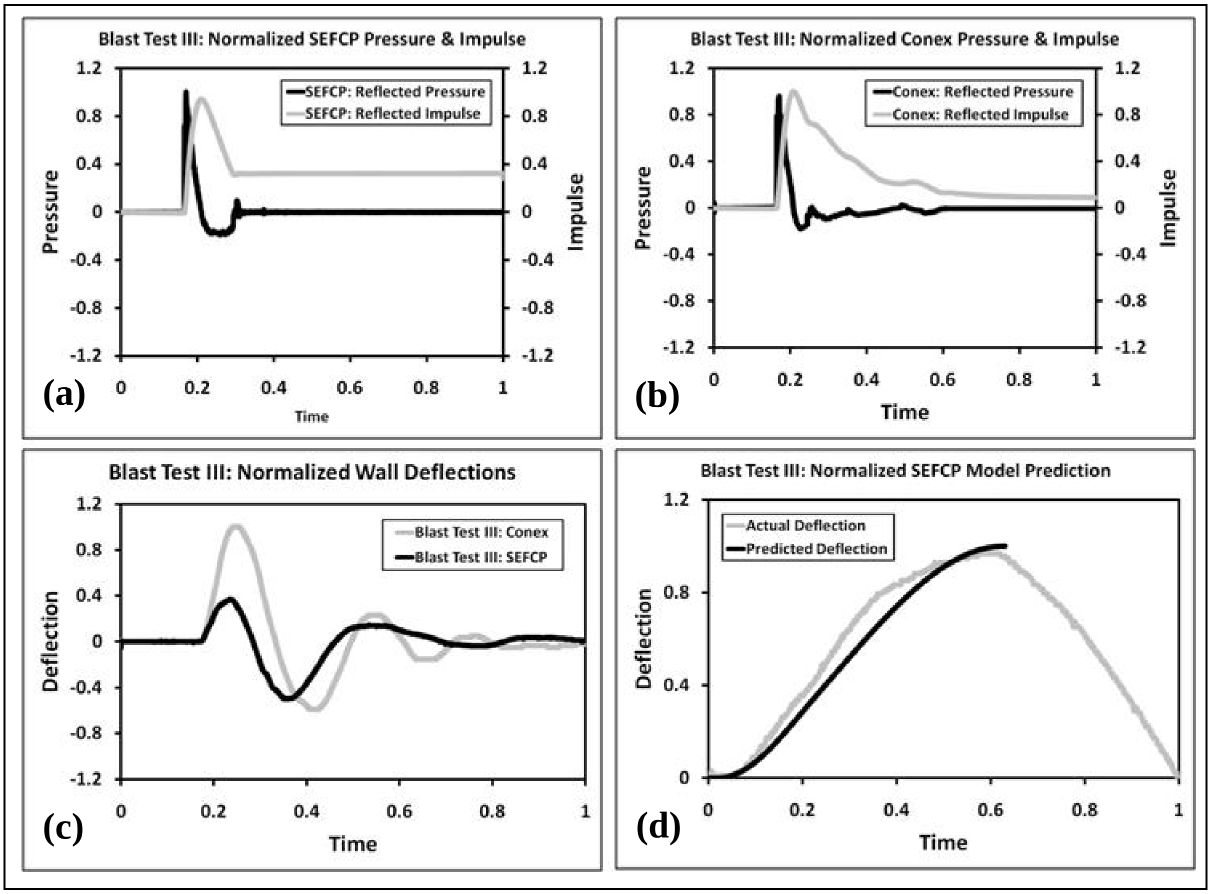

Figure 17. Blast Test III data: (a) SEFCP reflected pressure & impulse, (b) Conex reflected pressure and impulse, (c) Wall deflections, (d) SDOF model prediction.

Unlike the previous two tests, the SEFCP shelter suffered significant damage during Blast Test III. Each panel was halved and an autopsy was conducted to determine the extent of damage to the polystyrene core. As was the case during laboratory testing, shear failure of the core occurred approximately 18 inches from either end of the panels. Significant delamination of the steel skins was also apparent (Figure 18). Although some mechanical fasteners began to pull through the front face of the panels, none showed signs of failure. Again, minor rippling was observed in the Conex post-test.

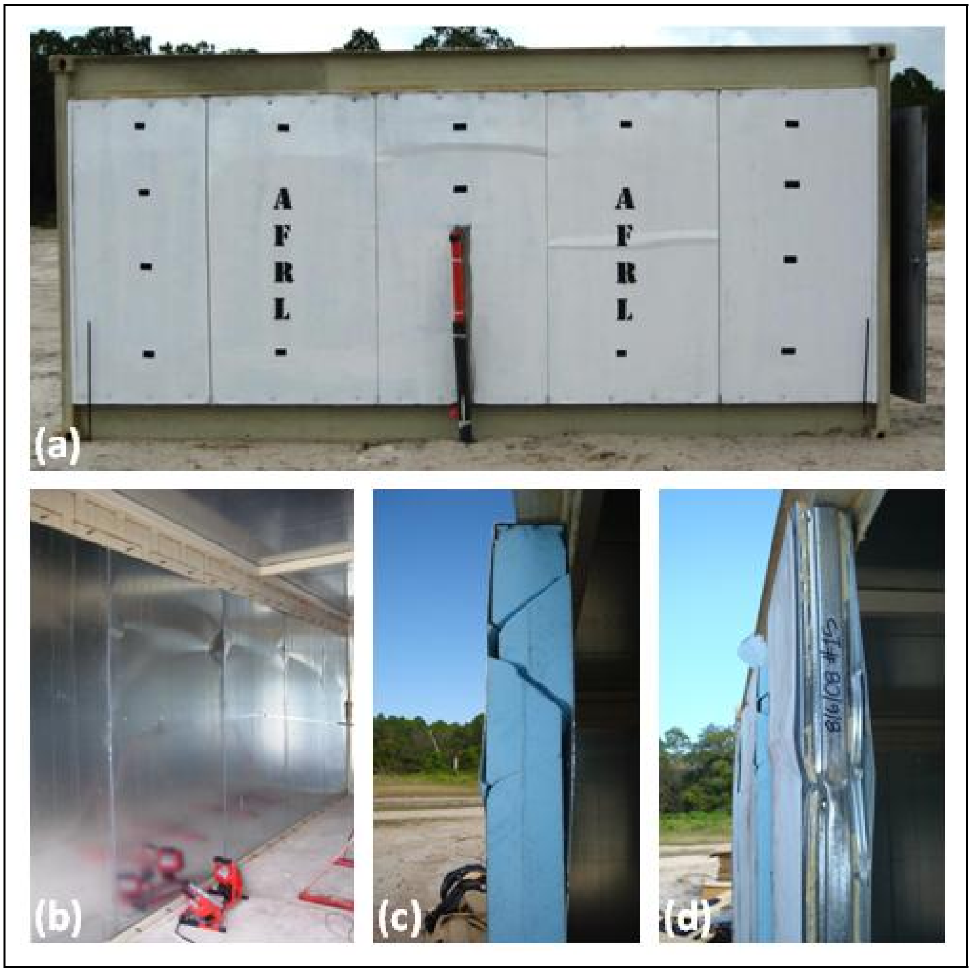

Figure 17. Blast Test III post-test damage: (a) External view, (b) Internal view, (c) Shear & delamination of foam core, (d) Deformation of edge profiling.

6. Conclusions

The focus of this investigation was to characterize to response of a newly developed expeditionary shelter when subjected to blast. SDOF modeling was employed to accomplish this objective with the first step being determining the static resistance function of the system. Resistance of the panels was determined in the laboratory via a loading tree and vacuum chamber. A 16-point loading tree was used to test several panel configurations employing various panel connection methods. In addition to testing commercially available connections, the resistance of an AFRL modified connection was also determined. This connection proved vastly superior to the commercial connection, increasing maximum resistance by 200%, and the energy absorption capability by 285%. Finally, a fixed connection was tested to determine the ultimate membrane capacity of the panel. In addition to the load tree testing, full-scale walls constructed of SEFCP panels were also tested in the vacuum chamber. The resistance of this system of panels was determined and compared to data from the loading tree. Ultimately, the dynamic response of the SEFCP shelter was modeled using a composite resistance function based on loading tree and vacuum chamber data. The model was validated by three full-scale blast tests. A Conex shelter was tested simultaneously to allow for direct data comparison

between the two analogous systems. The SEFCP shelter outperformed the ISO container in all three tests with approximately 68% less inward deflection. The SDOF model of the SEFCP shelter proved reasonably accurate when compared to actual blast data. Average percent error of the model was 12.4%.

7. Recommendations

Although the model predictions proved to be accurate for the three blast tests conducted over the course of this investigation, further testing is required to establish the protection level of the system across a broader spectrum of threats. Additionally, further care should be taken to replicate fielded conditions. When installed in the field, the SEFCP shelter is intended to sit on concrete footings and welded to steel base plates. Taking such a measure will ensure the maximum amount of energy from the blast will be imparted on the structures walls and not dissipated through system translation or rotation. Not only is the shelter designed to be secured to the ground, but the system is designed to be modular. A complex constructed of SEFCP shelters will present a much larger surface area to absorb blast energy. In such a scenario, clearing effects would be negated and the energy imparted to the structure will be significantly increased.

8. References

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